A MODEL FOR EXPLAINING SOME FEATURES OF SHUTTLE GLOW

Palmer N. Peters

Space Science Laboratory, Marshall Space Flight Center

Abstract. A solid state model is proposed which hopefully removes some of the objections to excited atoms being sources for light emanating from surfaces. Glow features are discussed in terms of excited oxygen atoms impinged on the surface, although other species could be treated similarly. Band formation, excited lifetime shortening and glow color are discussed in terms of this model. The model's inability to explain glow emanating above surfaces indicates a necessity for other mechanisms to satisfy this requirement. Several ways of testing the model are described.

Introduction

The predominant species striking forward facing shuttle surfaces in low-Earth orbits is atomic oxygen. The glow is reddish in color and excited oxygen has transitions that provide red emission. The glow is ram and altitude dependent and so is the flux of atomic oxygen to the surfaces. However, the emission from free excited oxygen atoms is observed in the form of sharply defined line spectra and the lifetimes of the excited states can be shown to be very long. Thus, it seems improbable that excited atoms, especially oxygen atoms, contribute to the observed glow, which produces a continuous band spectrum. Also, reflected oxygen atoms would de-excite at far greater distances from the surfaces than is observed, and if atoms were adsorbed they should be nonradiatively de-excited on the surface very quickly. This view of emission spectra from excited atoms is what should be expected, since atoms in a solid that are excited sufficiently to provide atomic spectra by means of an arc, or other sources, are already vaporized and the spectra originate from sharply defined energy levels associated with free atoms.

In the case of orbiting surfaces a unique situation exists which is not common to our experiences. Oxygen atoms and other species are incident to forward facing surfaces with sufficient energies to potentially excite such atomic states and enable the atoms to become part of a solid state at the same time. Solid state theories rely upon the fact that discrete energy levels of free atoms spread into energy bands upon assembly into solids.

The model to be described relies upon spreading of the energy levels of the atomic orbitals to provide the broadband emission and other features.

The Model

The relative velocity, in excess of 7 km/s, between forward facing orbiting surfaces and ambient particles provides a collisional interaction energy of 5 eV for oxygen atoms. This energy is considerably in excess of the 1.9 eV difference between the 1D and 3P states which leads to red emission lines at 6300 Å and 6364 Å (Figure 1). If losses during the collision were sufficiently low, then the 4.2 eV difference between the 3P normal state and the 1S state might be provided which leads to emissions in the green at 5577 Å and ultraviolet at 2972 Å. States requiring excitation energies greater than 5 eV are neglected for simplicity.

Also shown (Figure 1) is an approximation of the spreading that might be expected as discrete energy levels of a free atom are converted into energy bands of a solid. No attempt has been made to calculate densities of states for the poorly characterized case of an atom striking typical orbital surfaces, but the general trend can be noted by observing what occurs as progressively larger numbers of atoms are involved. Results for band calculations starting with six hydrogen atoms in a line show splitting of levels into six lines forming bands dependent upon lattice constant [Kittel, 1965]. Kittel also gives results for noble metals as a function of internuclear separation.

If specular reflection is assumed for an oxygen atom striking a surface with a speed of 8 km/s, it is easily determined that the atom would spend approximately 5×10^{-14} s within an atomic diameter on the surface. This is sufficient time for the atom to communicate at the speed of light with a large number of lattice atoms (within a hemisphere of radius 10^{-4} cm), which satisfies at least one requirement for producing many states within the bands. If it is necessary for the atom to become part of the lattice, it can be seen by comparison to self-diffusion coefficients that 5 eV minus 2 eV would leave sufficient energy to exceed most barriers to incorporation of the atom into a lattice (activation energies for self-diffusion are typically less than the 60 kcal/(g-atom) available from a kinetic energy of 3 eV [Askill, 1971]).

A broadband spectrum can be produced, assuming that the energy band structure is reasonably represented (Figure 1). Also, the peak intensity should be in the general vicinity of the discrete lines, though shifted, and have an asymmetrical distribution. A spectrum from STS 41-D [Mende et al., 1985] exhibits characteristics of this nature, with the peak shifted toward a longer wavelength and with a bandwidth in excess of 1.5 eV.

Model Testing

To test the model it seems appropriate that spectra of some type dependent upon solid state band structure should be compared to glow spectra. Soft x-ray emission spectra provide information on some band structures [Kittel, 1965] which arise when inner K and L levels are ionized by electron impact and outer electrons make transitions to the

inner vacancies. Since inner levels are relatively sharp because of shielding by the outer electrons, the bandwidths observed in the emission spectra are mostly due to the occupied width of the band from which the outer electrons made their transitions. The K emission band of lithium was found to have a full width of approximately 3 eV [Skinner, 1940], which should represent a good measure of the filled portion of the conduction band. Bandwidths of other materials are generally of the order 1 eV to 10 eV. Optical absorption coefficients versus wavelengths should also provide information about transitions between bands [Kittel, 1965]. Major absorption peaks for Cu and Au are 2000 Å to 3000 Å wide and peaked in the visible. Thus, the bandwidth for the glow is of the correct order compared to other spectra dependent upon solid state bandwidths (toward lower limit).

To provide a higher probability for glow from the surface the lifetime of the excited oxygen state should be less than the time spent traveling one atomic diameter during reflection ($<10^{-14}$ s, as mentioned earlier) or less than a period of lattice vibration ($\sim 10^{-13}$ s), if the atom is adsorbed. The exclusion principle $\Delta E * \Delta t \sim h$ provides a means of comparing linewidths to mean lifetimes [White, 1934]. Taking 0.7 eV for the half width of the spectral peak from STS 41-D data [Mende et al., 1985], and assuming the same uncertainty applies when $\Delta E = 0.7$ eV and Δt is the mean lifetime of the excited state, we obtain

$$\Delta t \sim \frac{h}{0.7 \text{ eV}} \simeq 6 \times 10^{-15} \text{ s} . \qquad (1)$$

In the derivation of pressure broadening of atomic spectra the collision damping contribution, which broadens the lines, has a correction added due to alteration of the energy levels due to the close approach of the second atom [White, 1934]. The initial and final states of the excited atom are not modified equally by collision since an excited, or outer, state is affected more than an inner tightly bound state. The effect is a shift toward lower frequencies for atoms emitting while spaced less than 10 Å. Asymmetry and redshifting of the spectral lines occur. This does not conflict in general with the appearance of the STS 41-D spectrum and the fact that a solid would produce greatly modified states.

Ground-based studies of airglow [Young, 1966] found a number of gases acted as quenching agents, reducing radiative de-excitations by collision losses. Carbon dioxide was particularly noted for this effect. If carbon dioxide or other contaminants have a high coverage on the surface, one might speculate quenching of the excitation or de-excitation of the incident atoms; this would provide for differences in glow intensities for different materials. Those materials producing a minimum of gaseous products, but exposing a cleaner, lattice-type structure might be expected to glow with more intensity (the opposite of what might be expected for chemical reactions providing the glow). The data from STS 41-D may show such a trend [Mende et al., 1985]. This could be further tested by using a high glow intensity surface coated with a thin plastic film. When the film is burned away, the glow should intensify. Using a half coated disk rotated behind an aperture and also phase-sensitive

detection would provide a low-noise measurement. Dosing of gases onto surfaces could also be used if limited so effects in the gaseous state above the surface did not dominate. If successful, such techniques (with acceptable gases or materials) might be useful for controlling shuttle glow. The distribution of oxygen atoms reflected from an orbiting surface (measurements by J.C. Gregory and P.N. Peters, to be published) may indicate a higher accommodation than would be predicted by hard sphere collision models. Mechanisms such as excitation/radiation which would deplete a large fraction of the particle's incident energy could help explain excessive accommodation coefficients where measured values exceed theoretical predictions. It should also be possible to measure incident energy thresholds for enhanced adsorption and glow if variable energy neutral oxygen atom sources are developed. If accommodation is found to be an adjustable parameter, numerous applications of this parameter to studies for understanding and controlling drag and torques in low-Earth orbits are possible.

As a solid state model, no mechanism is provided to explain glow emanating above surfaces.

Conclusions

A hypothetical solid state model appears to explain a number of features for glow emanating from a surface in low-Earth orbit. A specific case of oxygen atoms impacting the surface with 5 eV energy may provide the atom excitation, energy level broadening, and shortened lifetimes necessary to produce an appropriate spectrum. The model does not provide a mechanism for glow emanating above surfaces.

References

Askill, J., Tracer diffusion in metals, in Handbook of Chemistry and Physics, edited by R. C. Weast, 52nd ed., pp. F-48-F-51, The Chemical Rubber Company, Cleveland, Ohio, 1971.

Kittell, C., Introduction to Solid State Physics, 2nd ed., pp. 275-268, 318, 310, and 319, Wiley & Sons, New York, 1965.

Mende, S. B., et al., Shuttle glow measurements on STS 41-D, Final Report to Space Telescope Program Office, MSFC, Alabama, 1985.

Skinner, H.W.B., Trans. Roy. Soc., A239, 95, 1940.

White, H. E., Introduction to Atomic Spectra, pp. 423-432, McGraw-Hill, New York, 1934.

Young, R. A., The airglow, Scientific American, 214, 102-110, 1966.

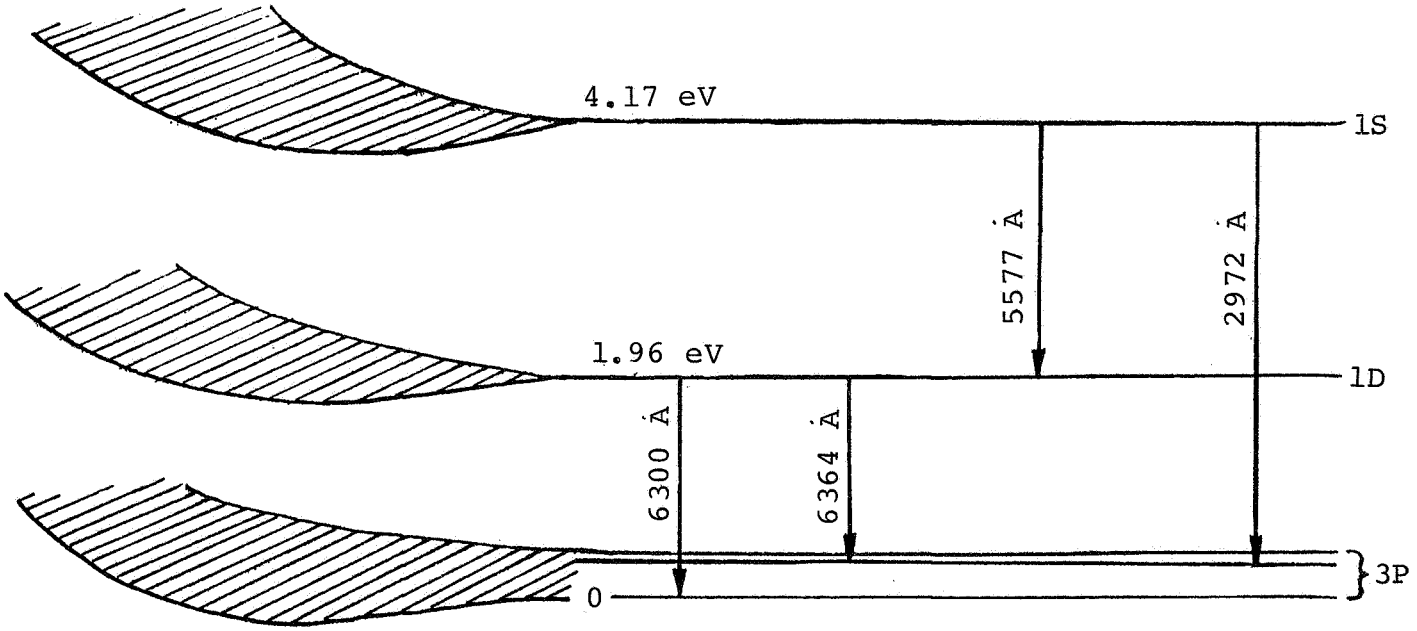

Fig. 1. A hypothetical representation of oxygen atom energy levels being spread on impacting surface.